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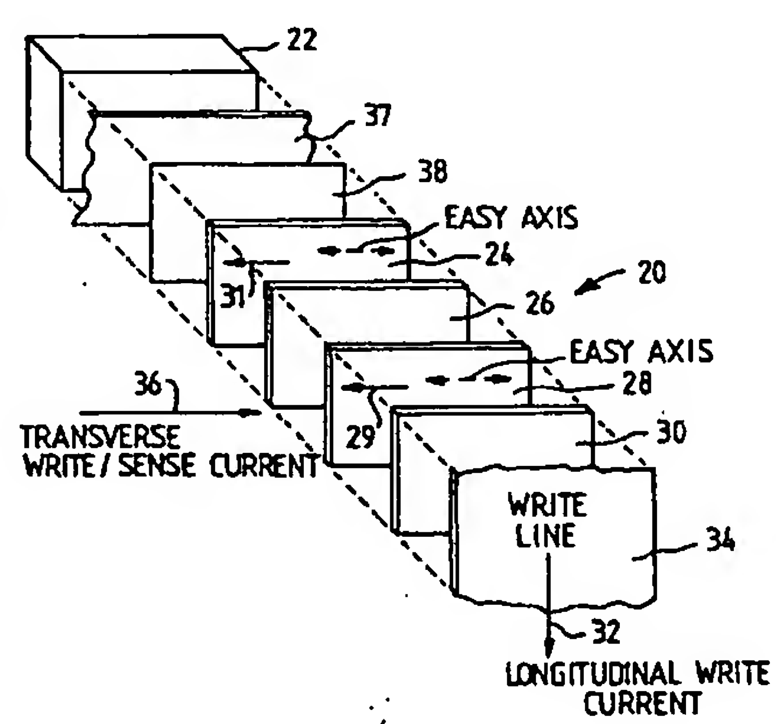
(54) Nonvolatile magnetoresistive storage device.

(57) A nonvolatile magnetoresistive (MR) storage device comprising a plurality of MR storage elements, each comprising a substrate and a multilayered structure including two thin film layers of ferromagnetic material separated by a thin layer of nonmagnetic metallic material. The magnetization easy axis of both ferromagnetic layers in each storage element is oriented substantially lengthwise of the storage elements and substantially parallel to the direction of an applied sense current. The magnetization direction of one of the ferromagnetic layers is fixed in a direction substantially lengthwise of the storage elements, and the magnetization direction of the other layer is free to switch between two digital states in which the magnetization is substantially parallel or substantially antiparallel to the magnetization direction in the one layer.

FIG. 2A
STATE 1



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This invention relates to high-performance, nonvolatile storage devices, and more particularly to a nonvolatile magnetic random access storage device using magnetoresistive storage elements with a spin valve configuration.

U.S. Patent 5,159,513 discloses a magnetoresistive (MR) sensor which utilizes the spin valve effect. The sensor comprises a rectangular multilayered structure deposited on a glass or other suitable substrate. First and second ferromagnetic layers are separated by a thin copper spacer layer. The magnetization of the first layer is fixed in a direction across the width of the sensor by use of a hard magnetic material as the first layer or, if preferred, by use of an antiferromagnetic layer to pin the first layer by exchange coupling. The magnetization of the second layer is normally in a direction along the length of the sensor, but is free to rotate through an angle determined by the magnitude of the magnetic field being sensed. Hence, the sensor is a analog type device.

A paper entitled "Enhanced Magnetoresistance in Layered Magnetic Structures With Antiferromagnetic Interlayer Exchange," published in Physical Review B of the American Physical Society, Vol. 39, No. 7, p. 4828, (1989), notes that antiferrromagnetic coupling between these layers results in a strong increase in magnetoresistance effect due to antiparallel alignment of the magnetizations in the ferromagnetic film layers, making this attractive for applications such as MR field sensors.

A paper entitled "Memory Implications of the Spin-Valve Effect in Soft Multilayers," published in J. Appl. Physics 69(8), 15 April 1991, at p. 5760 et seq., describes a MR storage element that also has certain deficiencies hereinafter to be more fully described.

There is a need for a nonvolatile magnetic storage device which overcomes these deficiencies, in that it (1) achieves a direct current read without requiring state interrogation, (2) utilizes the full $\delta R/R$ of the magnetic layers to achieve high sensitivity, (3) improves read access time by obviating the need for lock-in detection, (4) enables reduction in the size of the spin valve cell primarily by reducing the width of the MR storage element and thus increases the signal level, and (5) enables high-speed write and erase operations.

Viewed from one aspect the present invention provides a nonvolatile magnetoresistive storage device including at least one nonvolatile magnetoresistive storage element comprising: a substrate having a rectangular multilayered structure deposited thereon, including two layers of ferromagnetic material separated by a layer of nonmagnetic metallic material, the magnetisation easy axis of both ferromagnetic layers being oriented substantially lengthwise of the storage element, the magnetisation of one of the ferromagnetic layers being fixed in one direction substantially lengthwise of the storage element, and the magnetisation of the other ferromagnetic layer being free to change direction between substantially parallel and substantially antiparallel to the fixed one direction in response to an applied magnetic field.

In order that the invention may be fully understood a preferred embodiment thereof will now be described, by way of example only, with reference to the accompanying drawings in which:

Figs. **1A** and **1B** are exploded perspective views depicting the "1" and "0" information states of the last cited prior art MR storage element;

Figs. **2A** and **2B** are exploded perspective views depicting the "1" and "0" information states of an MR storage element embodying the invention;

Fig. **3** is schematic diagram of a 2x2 MR storage array depicting one implementation of the invention; and

Fig. **4** is a schematic diagram of a storage device embodying the storage array illustrated in Fig. 3.

Description of Prior Art

Figs. **1A** and **1B** depict an MR storage element of the type described in the J Appl Physics Reference. It comprises two ferromagnetic layers **11**, **12**, which are separated by a thin nonmagnetic spacer layer **14**. Note that the magnetization directions in the magnetic layers **11**, **12** as indicated by arrows 15, 16 (Fig. 1A) are antiparallel; that these magnetization directions both change substantially 180°, as indicated by arrows 17, 18 (Fig. 1B) in response to a write current; and that the easy access anisotropy is perpendicular to the direction of the sense current, as indicated by arrow 19.

Since the two magnetic states give identical direct current outputs, a longitudinal field provided by write/interrogation current 13 is required to dynamically interrogate the MR storage device to determine the existing state. To prevent destruction of the stored information as a result of switching of the states during reading, only a small rotation of the magnetization is permissible. This results in poor utilization of the $\delta R/R$ of magnetic sensor layers.

For example, in a one megabit array, the difference in rotation between the two states during a read operation corresponds to a $\delta R/R$ of 0.22%, which is less than 1/10 of the 2.5% total $\delta R/R$ of the multilayered structure. Also, the magnitude of the sense current must be limited to avoid inducing a change in state.

The combination of poor $\delta R/R$ utilization and low sense current results in low sensitivity, requir-

ing slow "lock-in" detection and, hence, a slow read access time.

This configuration is not extendable to very high density storage devices. This is because the shape anisotropy and edge curling domain walls hinder the transverse orientation of the magnetization. As a result, the width of the storage element cannot be made too narrow. If the size of the spin valve cell is reduced to reduce its width, the consequent reduction in length of the storage element would further reduce the already low signal level.

Description of the Preferred Embodiments

These deficiencies are overcome by applicants' novel spin valve cell configuration. As illustrated in Figs. **2A** and **2B**, storage element **20** embodying the invention comprises a suitable substrate **22**, such as glass, ceramic or a semiconductor, upon which are deposited a first thin film layer **24** of soft ferromagnetic material, a thin film layer **26** of a nonmagnetic metallic material such as copper, and a second thin film layer **28** of ferromagnetic material.

Note that the storage element **20** is rectangular, and that the easy access of magnetization is along the length of the storage element. The magnetization direction of magnetic layer **28** is fixed (see arrow 29) to be parallel to the longitudinal dimension of the storage element, such as by exchange coupling with an antiferromagnetic layer **30**. However, if preferred, the layer **30** may be eliminated provided layer **28** is of a sufficiently hard magnetic material or has sufficiently high anisotropy to retain its magnetization during state switching operations.

The magnetization of layer **24** is constrained by the uniaxial anisotropy and the shape geometry to lay in the longitudinal direction of element **20**, either parallel (see arrow **31**, Fig. 2A) or antiparallel (see arrow 33, Fig. 2B) to the fixed direction of magnetization of the layer **28**. Switching of the storage element **20** between the "1" state (Fig. 2A) and the "0" state (Fig. 2B) is accomplished by simultaneously applying a transverse field and a longitudinal field to element **20**. The longitudinal field is induced by a longitudinal write current **32** in a write line **34** provided by a conductor that extends orthogonal to the length of the storage element **20**. The transverse field is induced by a transverse write/sense current **36** flowing lengthwise through the element **20**. If desired to increase stability by enhancing the transverse field, additional transverse write/sense current may be provided via an optional separate conductor **37** that extends lengthwise through the storage element and is interposed between substrate **22** and an insulating layer **38** that contacts layer **24**, as shown only in Fig. 2A.

To ensure that the storage element **20** will exhibit only the two binary states, its short dimension should be smaller than the width of the magnetic domain walls. With a typical spin valve film thickness of 5.0×10^{-9}-9.0×10^{-9} metres (50-90Å), the Neel wall width is about 1.2µm indicating that a storage element width of 1µm or less should ensure viable transitions between the states. In an actual test, it was shown that a storage element having a 0.75µm width provided a single sharp transition between the parallel and antiparallel states. Electrical resistance is at a minimum when the magnetization of layer **24** is parallel to that of the fixed layer **28**, and is a maximum when the magnetization of layer **24** is antiparallel to that of the fixed layer **28**.

It will now be seen that the spin valve cell configuration of the storage element **20** achieves the previously stated objectives. Since the two states correspond to the maximum and minimum DC resistance due to the spin valve effect, the DC resistance can be detected and used directly for readout. No state interrogation is required, and a nondestructive readout is guaranteed.

The total δR/R of the magnetic layers **24**, **28** is utilized. For example, assume a typical spin valve structure of NiFe(90Å)/Cu(20Å)/NiFe(70Å)/MnFe-(120Å) and δR/R of 3.6% and a R of 20Ω/cm^2. With a storage element having a width of 1µm, length of 5µm, and a sense current of 5mA, the signal level is about 18mV, which is high enough to permit high speed real time detection and use in a one-megabit storage device. Further improvement can be achieved by reducing the cell size even more.

With the applicants' invention, there is no Barkhausen noise problem or linearity requirement. Materials, such as Co or other Co alloys, with high anisotropy/coercivity could enhance the stability of the storage element and increase the sensitivity two or three times.

Fig. 3 depicts storage cell selection circuitry for effecting read and write operations in a 2x2 storage array **40** embodying the invention. As illustrated, the array **40** comprises four identical storage cells **50A**, **50B**, **50C**, and **50D**, and two sense amplifiers **51X**, **51Y**. Each cell, **50A-D**, comprises an active MR storage element **52** and a reference MR storage element **53** to provide a differential output. To prevent shunting of a signal across the array, each storage element **52**, **53**, is energized by two sets of switches. For example, to write into cell **50A**, switches **55** of cell **50A** and 57 are closed, so that lines **B1** and **W1** are connected to allow write current to (**32**, Fig. **2**) flow through MR element **52** to induce a transverse field; and write line $\mathbf{W1^S}$ is connected to ground to allow current flow to induce a longitudinal field. To read the content of cell **50A**,

switches **55** of cell **50A** and **57** are closed to connect lines **B1** and **W1**, and switches **54** of cell **50A** and **56** are closed to connect lines **B1'** and **W1'** to allow sense current into both the active element **52** and the reference element **53** of cell **50A** and their differential output is sensed by amplifier **51X** as a differential output voltage.

It will thus be apparent that to write into cell **50B**, close switches **55** of cell **50B** and **54** and activate write current in **W2**^{S}; to write into cell **50C**, close switches **55** of cell **50C** and **59** and activate write current in **W1**^{S}; etc. To read out the content of cell **50B** into amplifier **51Y**, close switches **55** of cell **50B** and **57** to connect lines **B1** and **W2**, and close switches **54** of cell **50B** and **56** to connect lines **B1'** and **W2'**; to read out the content of cell **50C** into amplifier **51X**, close switches **55** of cell **50C** and **59** to connect **B2** to **W1**, and close switches **54** of cell **50C** and **58** to connect **B2'** to **W1'**; etc. Thus the combination of the two fields directed to a selectable one of the cells **50A-D** will induce switching in only the selected cell.

Fig. 4 depicts a storage device **60** embodying the storage cell array **40** shown in Fig. 3. When address bus 64 feeds an address to address decoder **62**, the decoder will activate the switches in the selected word lines and bit lines, so that a particular one of the cells **50-AD** in the storage cell array **40** is selected. If a read signal is transmitted via read/write select line 66, the content of the selected cell is interrogated and moved into the data I/O **68**, and later transmitted to data bus **70**. When a write command is received via read/write select line 66, the address decoder read/write control 62 will activate the switches and send a proper write current to the particular cell selected according to the information in data I/O 68 for writing data into that selected cell.

A nonvolatile magnetoresistive storage element has been described which comprises a substrate and a rectangular multilayered structure deposited thereon which includes two layers of ferromagnetic material separated by a layer of nonmagnetic metallic material. The magnetization easy axis of both ferromagnetic layers is oriented substantially lengthwise of the storage element. The magnetization of one of the ferromagnetic layers is fixed in one direction substantially lengthwise of the storage element, and the magnetization of the other ferromagnetic layer is free to change direction between substantially parallel and substantially antiparallel to the fixed direction in response to an applied magnetic field.

The width of the storage element is less than the width of magnetic domain walls of the layers of the multilayered structure.

The applied magnetic fields switch it between two states representing a logical "1" or a logical "0" according to whether the magnetization directions of the ferromagnetic layers are parallel or antiparallel, respectively. The magnetization direction of the one ferromagnetic layer may be fixed by exchange coupling with an antiferromagnetic layer; or, if preferred, this may be accomplished by use for the one layer of a hard magnetic material having a greater coercivity than the coercivity of said other layer, or sufficiently high anisotropy to retain its magnetization during state switching operations.

Viewed from another aspect the nonvolatile magnetoresistive (MR) storage device described comprises: a storage array comprising a plurality of MR spin valve cells, each cell comprising a substrate and a multilayered structured including two thin film layers of ferromagnetic material separated by a thin layer of nonmagnetic metallic material, the magnetization easy axis of both ferromagnetic layers in each cell being oriented substantially lengthwise of said cells and substantially parallel to the direction of an applied sense current, the magnetization direction of one of said ferromagnetic layers being fixed in a direction substantially lengthwise of the cells, and the magnetization direction of the other layer being free to switch between two digital states in which the magnetization is substantially parallel or substantially antiparallel to the magnetization direction in said one layer; means for producing a write current flow to switch a selectable one of said storage elements from one of said states to an opposite state for writing data; and means for applying the sense current to sense the state then existing in a selectable storage element for reading the data therein; an address bus; an address decoder and read/write control means interposed between and connected to said address bus and said storage array; a data I/O device connected to said storage array and data bus; and a read/write select line for selectively conveying read and write signals to said decoder and read/write control means, for conditioning the latter, (i) in response to a read signal, to interrogate the data in a selected cell corresponding to an address received from the address bus and conditions said array to enter said data into the data I/O device, and (ii) in response to a write signal, to condition said array to cause to be written into a selected cell data corresponding to data received from the data I/O device.

While the invention has been shown and described with reference to a preferred embodiment thereof, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the scope of the invention.

Claims

1. A nonvolatile magnetoresistive storage device including at least one nonvolatile magnetoresistive storage element comprising:
   a substrate having a rectangular multi-layered structure deposited thereon, including two layers of ferromagnetic material separated by a layer of nonmagnetic metallic material, the magnetisation easy axis of both ferromagnetic layers being oriented substantially lengthwise of the storage element, the magnetisation of one of the ferromagnetic layers being fixed in one direction substantially lengthwise of the storage element, and the magnetisation of the other ferromagnetic layer being free to change direction between substantially parallel and substantially antiparallel to the fixed one direction in response to an applied magnetic field.

2. A nonvolatile magnetoresistive storage device as claimed in claim 1 wherein the width of the storage element is less than the width of magnetic domain walls of the layers of the multilayered structure.

3. A nonvolatile magnetoresistive storage device as claimed in any of claims 1 or 2 further comprising means for applying magnetic fields to a storage element for switching it between two states representing a "1" or a "0" according to whether the magnetisation directions of the ferromagnetic layers are parallel or antiparallel respectively.

4. A nonvolatile magnetoresistive storage device as claimed in any of the preceding claims wherein the width of each storage element is less than the length of the storage element by an amount sufficient to ensure that said other layer will remain in a selected domain state.

5. A nonvolatile magnetoresistive storage device as claimed in any of the preceding claims wherein the electrical resistance is at a minimum or a maximum according to whether the magnetization of said other layer is substantially parallel or substantially antiparallel, respectively, to the magnetization of said one layer.

6. A nonvolatile magnetoresistive storage device as claimed in any of the preceding claims, further comprising an antiferromagnetic layer for magnetizing said one layer in said fixed one direction by exchange coupling.

7. A nonvolatile magnetoresistive storage device as claimed in any of the preceding claims wherein said one layer is of a hard magnetic material having greater coercivity than the coercivity of said other layer.

8. A nonvolatile magnetoresistive storage device as claimed in any of the preceding claims wherein said one layer has sufficiently high anisotropy to retain its magnetization during state switching operations.

9. A nonvolatile magnetoresistive storage device as claimed in any of the preceding claims comprising:
   a plurality of spin valve cells, each cell comprising two of the nonvolatile magnetoresistive storage elements, one being an active storage element and the other a reference storage element;
   at least one differential amplifier; and
   means for supplying sense current via the active and reference elements of a selectable one of the cells to an associated amplifier to provide a differential output voltage of a magnitude denoting the then current magnetic state of the selected cell.

10. A nonvolatile magnetoresistive storage device as claimed in claim 9, including means for applying to a desired one of the cells a write current that flows in a direction orthogonal to the direction of the sense current while concurrently supplying the sense current solely to the active element of the desired cell, for storing data in the desired cell.

11. A nonvolatile magnetoresistive storage device as claimed in any of claims 9 or 10 wherein the sense current induces a transverse magnetic field and the write current induces a longitudinal magnetic field, for thereby writing a "1" or a "0" in the selected cell according to whether the magnetization directions of the ferromagnetic layers of said active storage element are substantially parallel or substantially antiparallel, respectively.

PRIOR ART

FIG. 1A

STATE 1

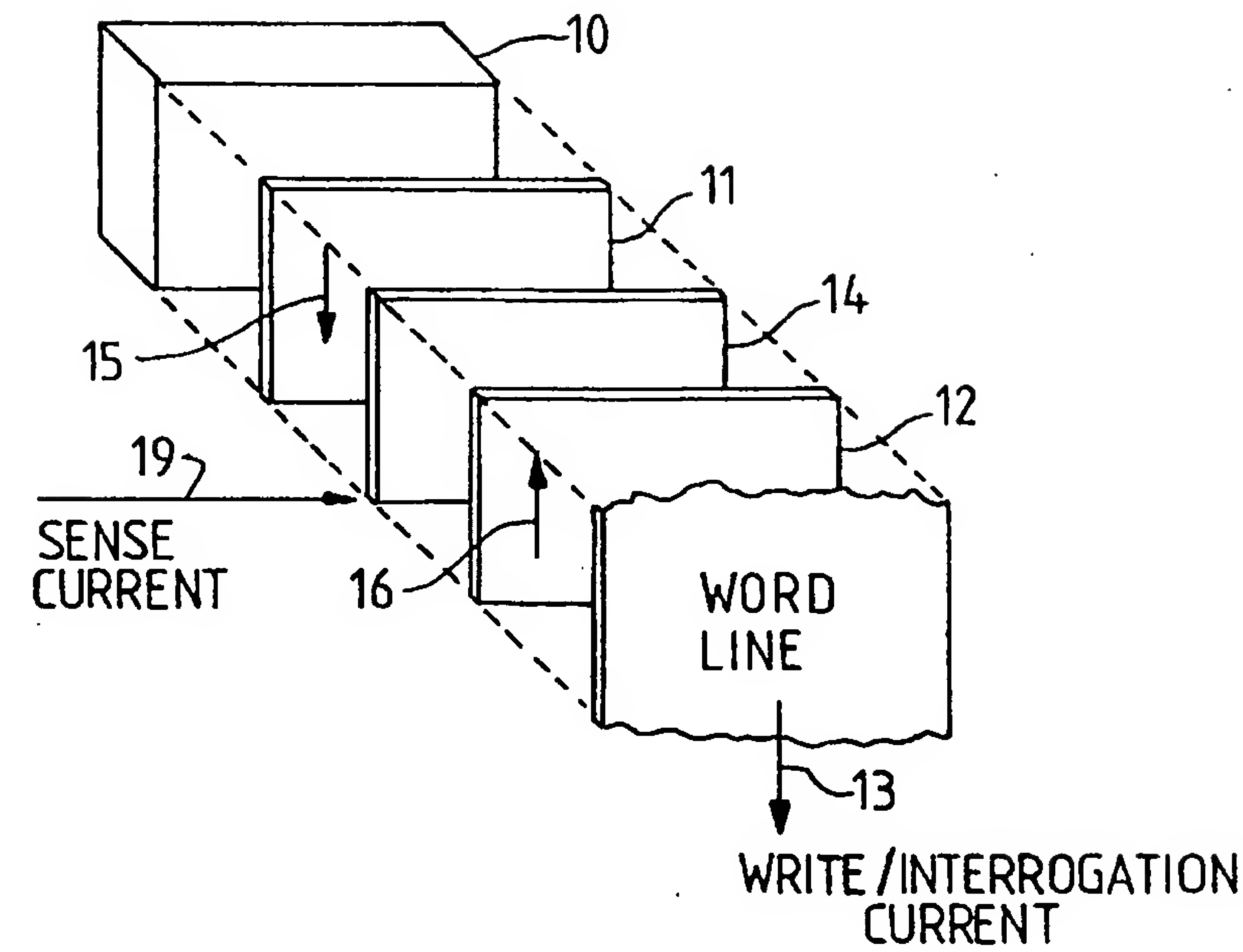


FIG. 1B

STATE 0

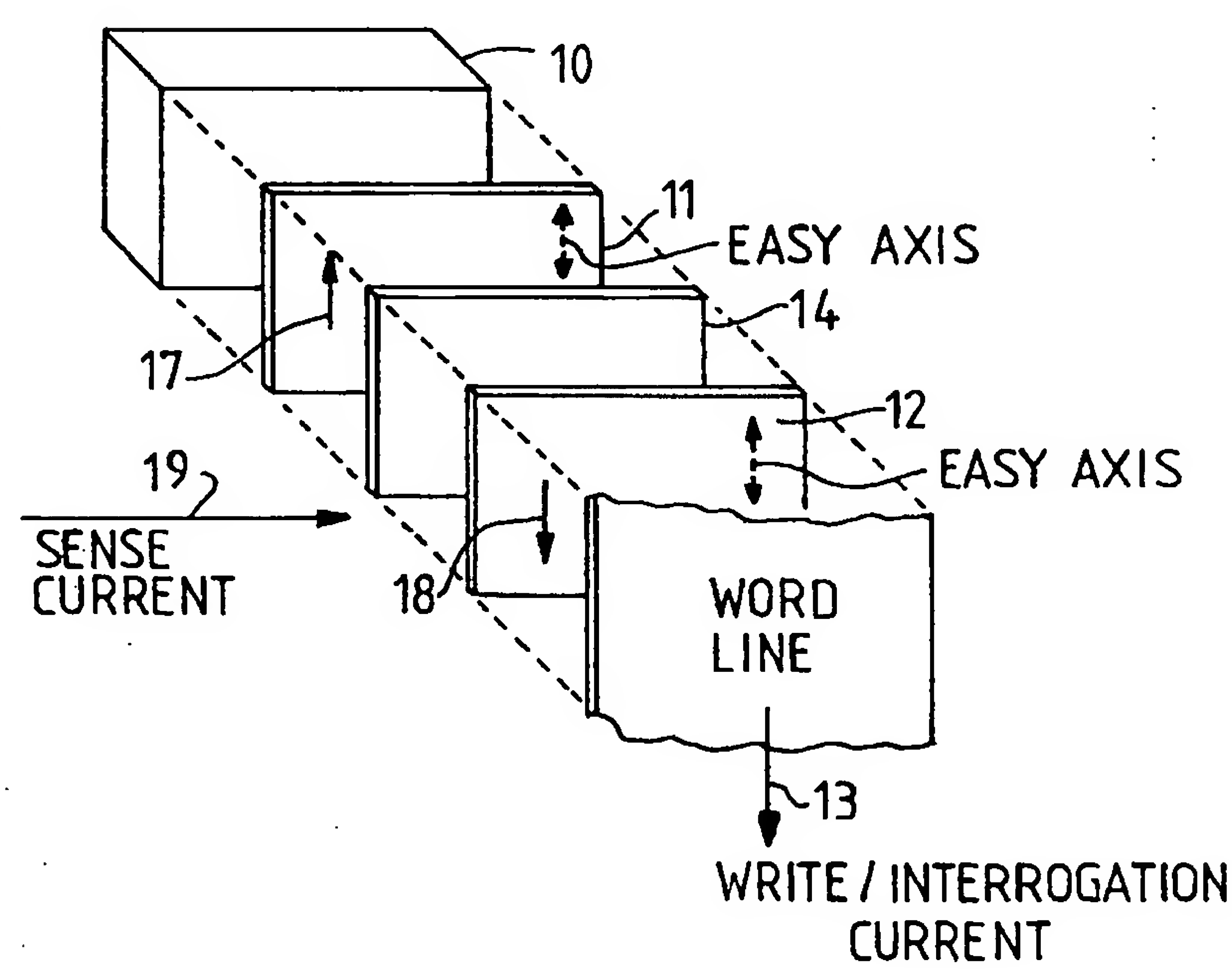


FIG. 2A

STATE 1

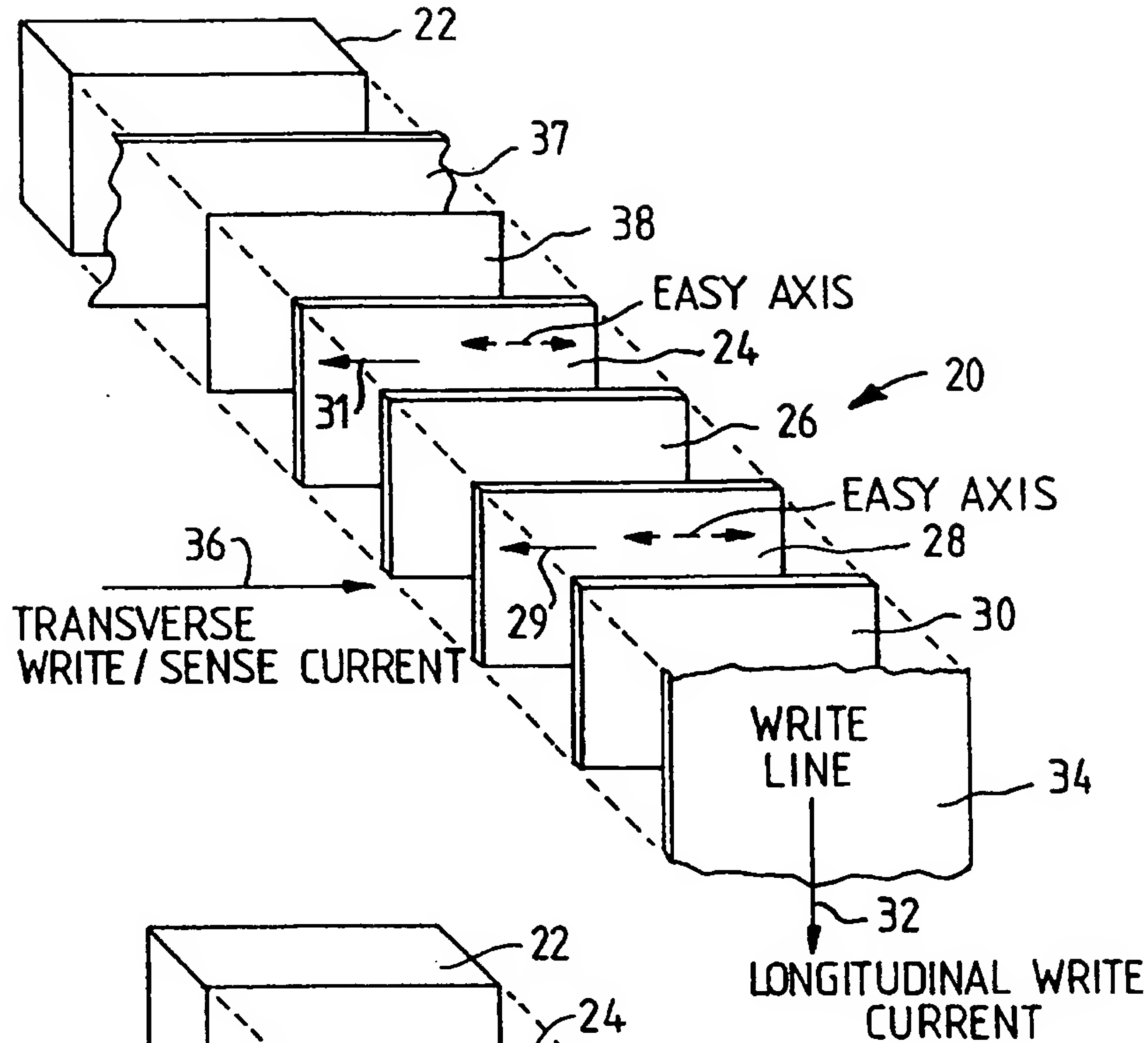
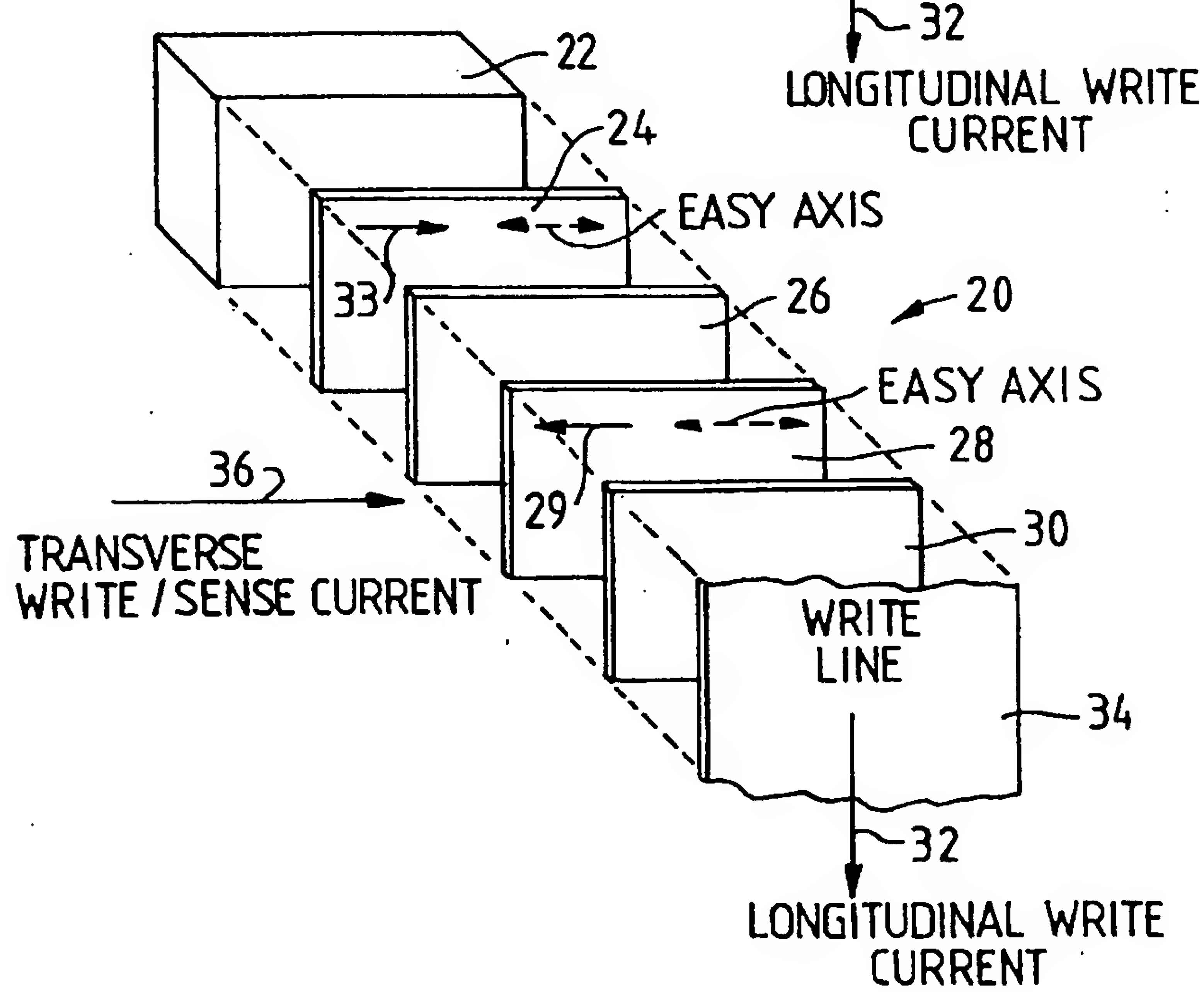


FIG. 2B

STATE 0



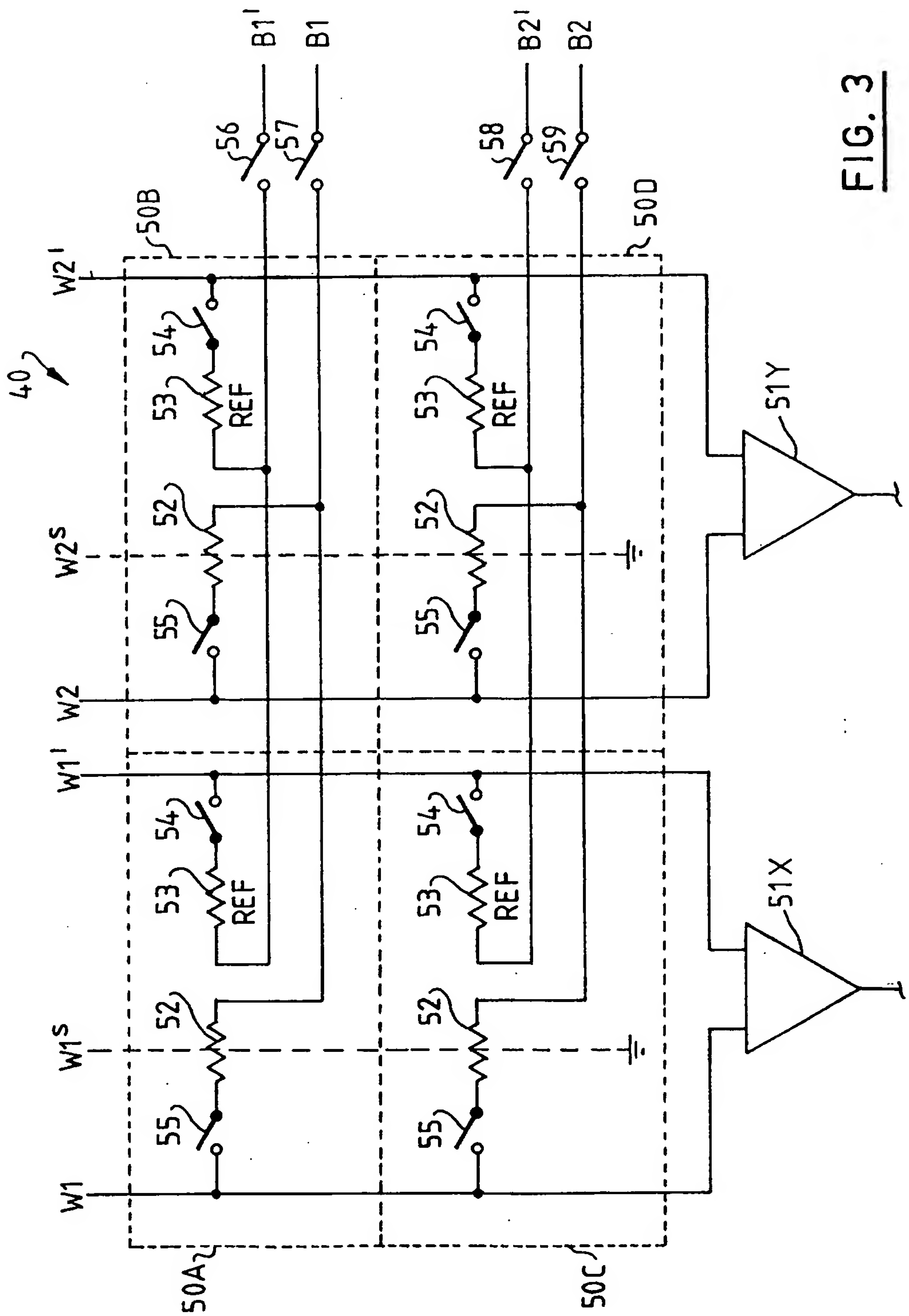

40
W1
W1S
W1'
W2
W2S
W2'
B1'
B1
B2'
B2
50A
50B
50C
50D
51X
51Y
52
53
54
55
56
57
58
59
REF

FIG. 3

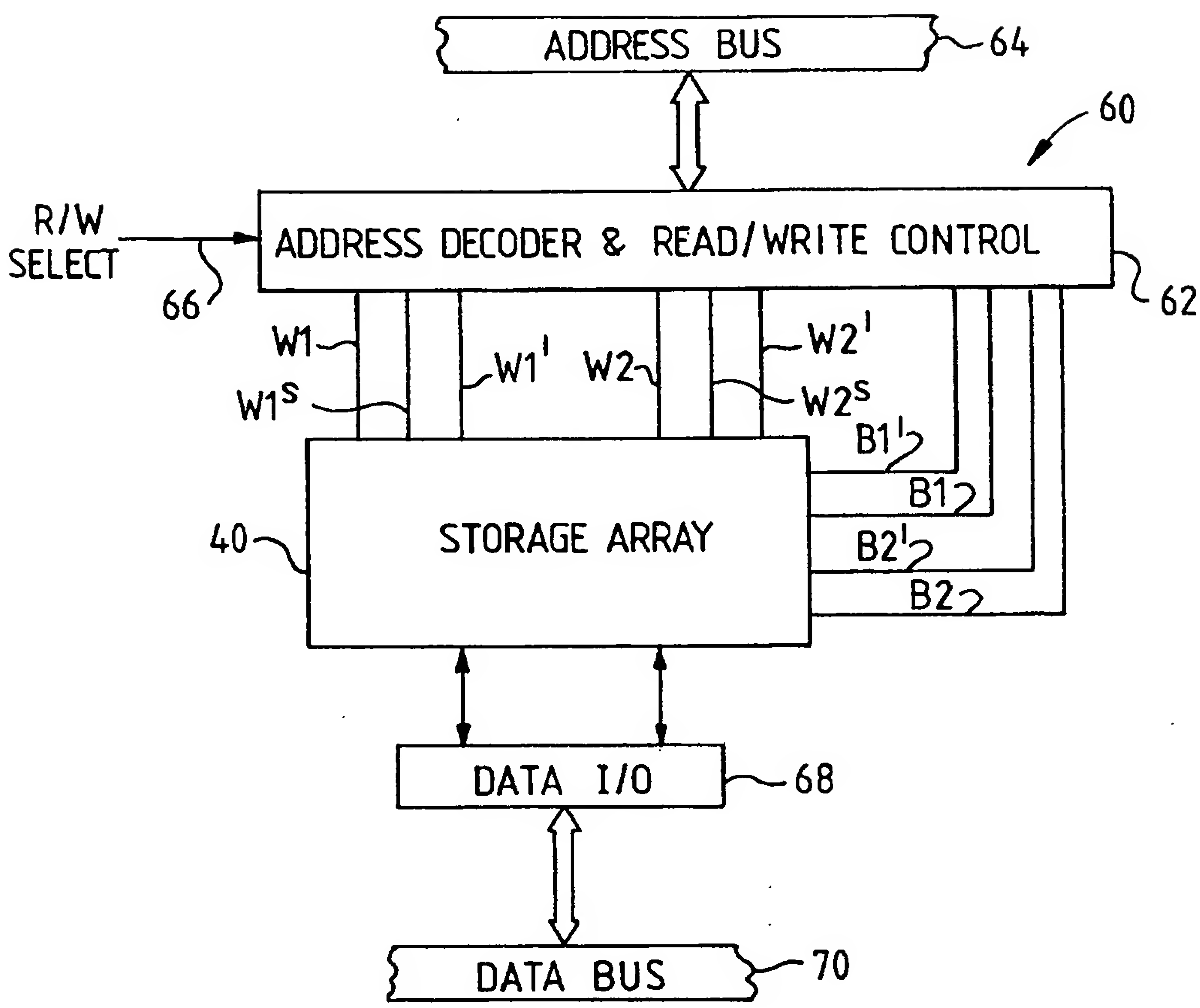

ADDRESS BUS
64
60
R/W SELECT
ADDRESS DECODER & READ/WRITE CONTROL
66
62
W1
W1'
W2
W2'
W1S
W2S
B1'
B1
B2'
B2
40
STORAGE ARRAY
DATA I/O
68
DATA BUS
70

FIG. 4